Field-effect P-N Junctions

- for Low Cost, High Efficiency Solar Cells and Electronic Devices

Commercial Analysis

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Technology

The majority of current commercial solar cells rely on p-n junctions – interfaces between electron-depleted and electron-rich regions – to extract photo excited charge carriers. Professor Alex Zettl's lab has created a novel method for p-n junction formation: "screening-engineered field-effect photovoltaics' (SFPV). SFPV uses a gate-induced electric field to control the flow of charge in a semiconductor.

Applications

SFPV is a technology specifically designed for a solar cell. It adopts well-known gating processes from the transistor industry and applies them to a solar cell. The key innovation for the SFPV technology is overcoming the problem of gate screening. As a light emitting diode is essentially a solar cell in reverse (it takes in electricity and emits light rather than taking in light and produces electricity), LED cells are a second potential application. As SFPV is material agnostic, application in both Silicon and thin film (CdTe and CIGS) cells is possible.

As is illustrated below, SFPV technology avoids gate screening, and an analogy is the comparison to how an actual "porous" household gate lets light through.

Figure 1: SFPV solution to gate screening

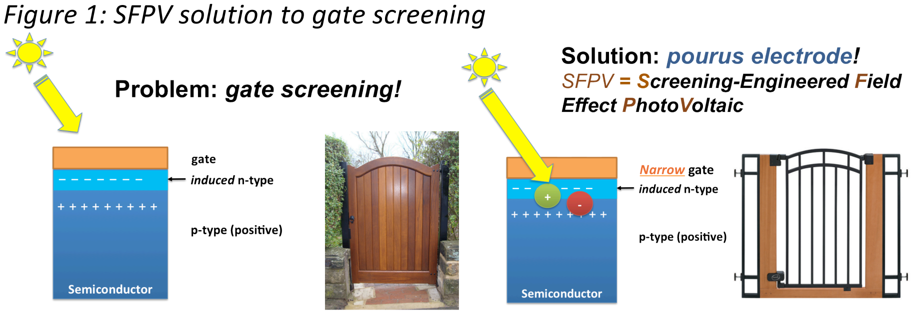


Table 1 - Applications of LBNL's SFPV technology

Technology	Material
Solar Cell	Silicon
	Thin Film (CdTe & CIGS)
LED Cell	

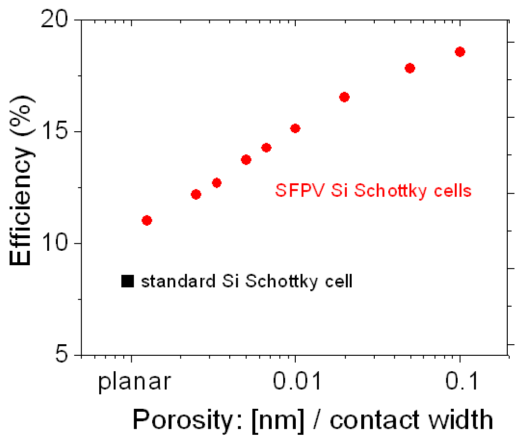
SFPV Increases Efficiency

The Zettl lab has created computer models to predict the efficiencies of SFPV cells and has verified these predictions experimentally using Si Schottky barrier cells as a proof of concept.[1] Based on a preliminary computer simulation developed by the lab, researchers believe that SFPV could increase the efficiency of an optimized Si Schottky cell from 8% to over 18% by using SFPV, as illustrated in Figure 2.

[1] Regan, Byrnes, Gannett, Ergen, Vazquez-Mena, Wang, and Zettl, *Screening-Engineered Field-Effect Solar Cells*, NANO LETT.,12 (8) 4300-4304 (2012).

In addition, the SFPV design is potentially a "universally-applicable doping method," which uses an applied electric field to modulate the local semiconductor free charge carrier density and type. The lab believes that SFPV could increase solar cell efficiencies in other materials such as CIGS, CdTe, and in non-traditional solar architectures such as Metal-Insulator-Semiconductor (MIS) solar cells.

Figure 2: Theoretical Efficiency of Optimized Si Schottky Cell using SFPV



Additional Technical Detail

SFPV is novel in that it uses a partially-screening top-electrode to tune the electrode-semiconductor junction. Using a field effect to control charge in PV is not new; however, previous methods have been limited by screening of the gate. SFPV solves the problem of screening of the gate and demonstrates an electrically contacted p-n junction formation on nearly any combination of semiconductor and electrode material. The key innovation is 'minimal screening,' whereby the top contact and gate are physically separated and thus may be optimized for high visible light transmission and high conductivity.

Market

<u>Solar Modules</u>

Table 2: Projections for Cumulative and Annual Installations of Solar Capacity

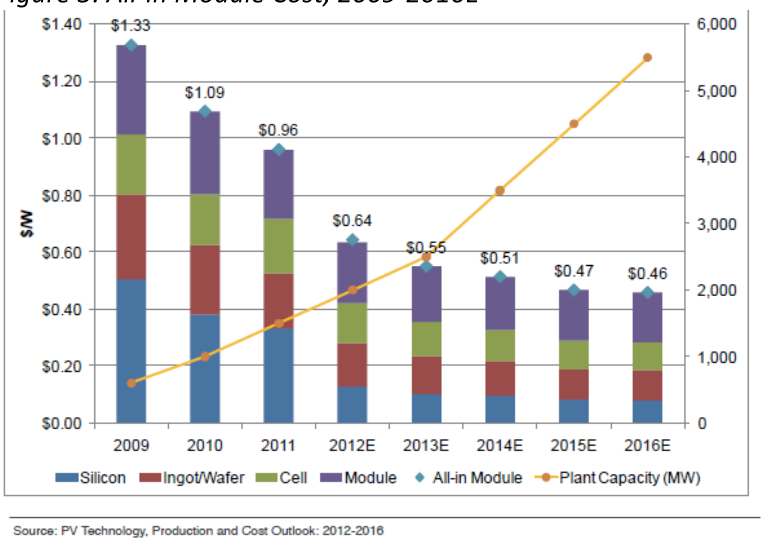
Capacity	2011	2012	2013	2014	2015	2016	2017
Global Solar Capacity (GW)	70	91	115	140	167	197	230
CSP Solar Capacity (GW)	2	4	5	7	8	10	11
PV Solar Capacity (GW)	68	88	110	134	159	188	219
PV Solar New Installs (GW)	30	20	23	24	26	29	32

Sources: IEA World Energy Outlook and BP Statistical Review 2012

In 2017, IEA projects new demand for PV solar to be approximately 31.5 GW. However, the choice to develop SFPV for silicon or thin-film cells will determine what portion of the PV solar module demand the technology can integrate into.

The second variable in estimating total addressable market is the expected selling price for silicon PV modules. While recent trends in module prices have been artificially suppressed, manufacturing costs will continue to decline. For example, according to analysis by Greentech Media, manufacturing costs for silicon modules in 2016 are expected to be $0.46 per watt.

Figure 3: All-in Module Cost, 2009-2016E



Source: Greentech Media, PV Technology, Production and Cost Outlook: 2012-2016

At a 10% gross margin, the average selling price of PV modules is projected to be approximately $0.50 per watt by 2017, which is also the Department of Energy's SunShot program target for solar grid parity, the price at which solar can economically compete in the electricity markets on an unsubsidized basis.

Table 3 shows these basic calculations to arrive at projected addressable markets in 2017.

Table 3: Projected Module Market Size in 2017

	Silicon	Thin-film
Module demand (GW)	28.4	3.2
x Module selling prices ($/W)	$0.50	$0.50
= Module market size ($bn)	$15.8	$1.6

Source: International Energy Agency, Greentech Media, team assumptions

Solar Manufacturing Equipment

A second monetization route is for solar module fabrication equipment manufacturers to license the technology from Berkeley Lab, develop the new equipment necessary to produce solar cells with SFPV, and then sublicense the Berkeley Lab technology to solar module manufacturers.

In order to estimate the potential equipment market in 2017, historical investment patterns of the largest PV module manufacturers were analyzed. As illustrated in Table 4, companies have invested roughly 20-25% on average in capital expenditures from 2006 - 2011.

Table 4: Historical CapEx/Sales of PV Module Manufacturers

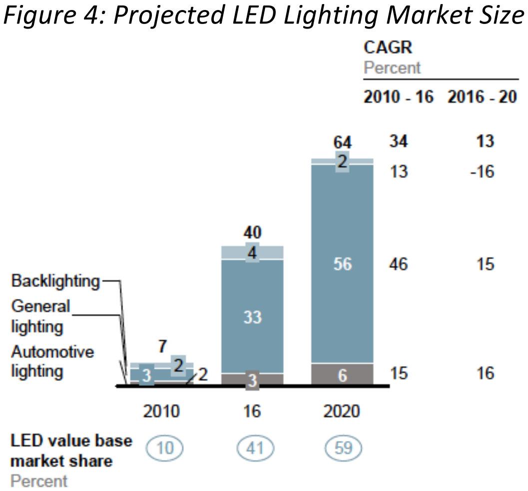
CapEx/Sales	2011	2010	2009	2008	2007	2006
First Solar (Thin-film)	26%	23%	14%	37%	48%	113%
SunPower	6%	5%	11%	19%	25%	42%
Trina	18%	8%	16%	20%	41%	36%
Suntech	12%	10%	8%	17%	12%	9%
LDK	46%	23%	68%	68%	58%	69%
Hanwha SolarOne	37%	8%	7%	17%	21%	28%
JA Solar	21%	14%	16%	15%	16%	15%
Yingli	33%	25%	31%	26%	24%	34%
Canadian Solar	11%	9%	11%	15%	14%	10%
Jinko Solar	27%	28%	15%	15%		
Average	22%	15%	20%	28%	26%	32%
Median	23%	12%	15%	18%	24%	34%
High	46%	28%	68%	68%	58%	113%
Low	6%	5%	7%	15%	12%	9%

Source: Bloomberg

LED

The LED market is significant and rapidly growing, with over 7 billion euros revenue in 2010. Growth through 2020 is expected to be 13% annually, resulting in 64 billion euros in 2020, 56 billion of which is expected from general lighting, with the remainder in backlighting and automotive lighting.

Figure 4: Projected LED Lighting Market Size by Sector



Source: McKinsey Global Lighting Professionals & Consumer Survey

Intellectual Property

Patent pending. The technology is available for licensing or collaborative research.

Licensing Strategy

While the SFPV IP could potentially be broadly licensed, this approach has been nearly non-existent in the solar PV industry. As further development will be required, a joint development agreement with a manufacturer and exclusive license is likely the most attractive option for developing and commercializing the SFPV technology.

Next Steps

Companies interested in licensing this technology may contact ttd@lbl.gov or call 510-486-6457.